BAAM - Large Scale Additive Manufacturing

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Fused Deposition Modeling
Polymer Additive Manufacturing
Economics of AM

- **Material**
  - Material cost per kg is typically $100 to $200/kg
  - Material cost per part is typically 1.1*volume of part to cost/kg

- **Pre-Processing cost**
  - Operator cost/hr * setup time/number of parts produced
  - Setup includes support and slicing software, prep of machine

- **Processing cost**
  - Typically machines are between $500K and $2M
  - Operation time is typically 5000 hours per year
    - Note, there is cool down time for some machines
  - Machine cost per build. Typical hourly rate is $250/hr

- **Post processing cost**
  - Part cleanup, machining, heat treatment
Residual Issues in FDM AM

- Additive Manufacturing is:
  - Slow: Deposition Rates ~ 1-2 ci/hr
  - Expensive: Material Cost ~ $2.25/ci or ~$58/lb (ABS)
  - Small Parts: Largest Workspace 3’ x 2’ x 3’ (31,104 ci)
    - 3.5 Years to build a part that takes up the full volume at 1ci/hr
Legacy Work in Large Scale Deposition – Additive Construction

Demonstration of Automated Freeform Construction

Robotics and Energetic Systems Group

Oak Ridge National Laboratory
Unique Advantages of Additive Construction

- Better material utilization and reduced waste
- Use more durable materials
- Little or no finish treatments required
- High build accuracy – no air leaks
- Integrated combinations of materials and reinforcements
- More optimum geometry/materials
  - Thermal efficiency
  - High strength/weight
  - Wireways, ducts built in
- Low additional cost for increased complexity
- Reduced Labor
- Design freedom
  - Curves
  - Hollow structures
  - Aesthetics
  - Interior and exterior finishes
Big Area Additive Manufacturing (BAAM)

Large scale deposition system
- Unbounded build envelope
- High deposition rates
  - (up to 40 lbs/h, >1000ci/hr)
- Direct build components
- Tools, dies, molds

Carbon fiber material reduces warping out of oven
Process Modifications

- Material Supply
  - Pellets not Filament
  - Low Cost Injection Molding Plastics
    - $1 - $5 /lb
  - Purchase by the Gaylord (1000lb)
Process Modifications

- Extrusion
  - Single Screw Extruder instead of a Heated Nozzle
Low Hanging Fruit - Tooling

• NavAir Cherry Point
  – Legacy aircraft tooling for sheet metal manufacturing
  – Part model sent on Monday
  – Parts printed on Tuesday
  – Machined Wednesday and shipped
  – First parts made on Friday

• Took Longer and Cost More to Ship than to Make
Thermal Imaging of BAAM
Partnership with CRADA

ORNL and Cincinnati Incorporated collaborate to create commercial large-scale system

Partnership to establish US-based large-scale AM equipment manufacturer

- Targets tooling lead time and cost reduction
- Cincinnati providing >$1M in cost share year one
  - First large-scale polymer AM system delivered to MDF, April 2014
  - Operational mid-May 2014
- Interest from multiple automotive, aerospace and tooling industries
- Stretch form and hydroform tools demonstrated
- Program started Jan 2013. Goal is commercial product Jan 2015 (24 months)
CI BAAM Development Timeline

**ORNL & Cincinnati Inc. Sign CRADA**
- Cincinnati Inc. Delivers Alpha I to MDF

**ORNL Prints 1st Part on BAAM**
- Team Begins Software Dev.

**Support Generation Solved**
- Support Generation Solved

**Alpha II Sold and Delivered to Chicago**
- Alpha II Build Started

**Local Motors Releases Design Challenge**
- ORNL & Local Motors Sign CRADA (Set IMTS Goal)

**Test Vehicle Works!**
- ORNL & LM Print Test Vehicle

**MDF Receives Strati Model Ver. 1**
- MDF Receives Strati Model Ver. 1
-的新螺钉

**ORNL & LM Start Test Car Prints**
- ORNL & LM Start Test Car Prints
  - Ver. 1
  - Ver. 2
  - Ver. 3

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13 SPARK – Additive Manufacturing

MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY
CI BAAM Development Timeline
Support

[Image of two people working in a facility, possibly with equipment or a large component.]
Test Car #1

- 7 Days and Nights of Printing
- 1500+ lb of Plastic
- Layer Times > 60 mins

-> DELAMINATION
Finishing and Assembly

Printing Time: 47 hrs
Finishing Time: 12 hrs
Assembly Time: ~ 16 hrs

On the Seventh Day It Drove
AMO – VTO 3D Printed Shelby Cobra

- **Next Generation Lab on Wheels**
  - Demonstrator for Advanced Vehicles Technologies
    - Wireless Charging
    - Vehicle Control Systems
    - High Performance Motors
    - Integrated Energy Systems
  - Rapid Design and Manufacturing
    - Small Team in a Short Period of Time (6 Weeks)
  - Hardware in the Loop Modeling for Drivetrain Integration
    - All components and controls tested under typical driving scenarios prior to integration
Cobra

SHELBY COBRA PRINT 2014

RAPID INNOVATION

ENERGY EFFICIENCY

1700 Btu per pound of printed material

0.2 in. diameter nozzle results in a 0.020 in. surface variation

Class A final surface finish through machining, sanding, and polishing.
Rapid Progress in BAAM

• January 2013: Prototype system at ORNL
  – 7’ x 7’ x 5’ build volume
  – 10 lb/hr deposition rate

• September 2014: Alpha CI-BAAM
  – 7’ x 13’ x 3’ build volume
  – 40 lb/hr deposition rate

• July 2015: Beta CI-BAAM
  – 8’ x 20’ x 6’ build volume
  – 100 lb/hr deposition rate
High speed/ high profile demonstrations

- Local Motors Strati – first 3D printed car (Sept 2014)
- ORNL AMIE – printed car and house, bidirectional wireless power transfer (Sept 2015)
- Printed Cobra – first finished parts (Jan 2015)
- Printed Jeep for OSD – Fast application coatings (Nov 2015)
- Printed Trim Tool for Boeing – Guinness Largest Printed Object (Aug. 2016)
- Printed Composite tooling for NavAir – High temp materials (Nov 2015)
- Printed wind turbine mold – TPI (April 2016)
Demo wind turbine mold project

- Objective – demonstrate feasibility of using BAAM to manufacture wind turbine mold. Quantify costs and explore potential for significant manufacturing cost reduction

- Mold is one component of a large program exploring variable blade designs to increase efficiency in field due to eddy currents (led by Sandia)

- Project will result in manufacture of 13 m blades to be installed and tested in Swift facility
**Mold Fabrication: Heating (1)**

**Integral air heating**
- Ducts designed into support structure for mold form
  - Eliminates embedded wiring and electronics
  - One printed piece has structure, ducting and interfaces to truss structure
- Integral commercial inline blowers/heaters complete the system
  - Flexible, reusable - blowers and heaters can be transferred from mold to mold as opposed to embedded into each mold permanently
- Confident strategy applicable for full mold.
Mold Fabrication: Heating tests (2) - GREEN

- Utilized 14 thermocouples (baseline measurements), thermal imaging and laser scanner to measure temperature and surface variations during heating
  - Experimental validation
    - Thermocouple data
    - Laser profilometry data
    - Thermal cycling trials

Results from all tests meet design requirements

Experimental setup
Laser tracker in foreground
Thermal imaging on mold surface
## Wind Turbine Molds

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<th>Traditional 50 m Mold</th>
<th>3D Printed 50 m Mold</th>
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| Fabrication takes a total of **27 weeks**  
• 12 weeks: fabricate plug  
• 3 weeks: setup and inspect to confirm shape  
• 6 weeks: layup shell, attach frame, demold from plug  
• 6 weeks: Electrical connections, cure, QA, shipping prep | Based on 13 m mold results, a 50 m mold can be designed, printed and finished in only **20 weeks**  
• 12 weeks: print mold sections  
• 4 weeks: glass and finish mold sections  
• 4 weeks: attach frame, install heaters, QA, shipping prep |
| 1 pair of main plugs – reliable for 6 to 10 molds. On pair of molds typically reliable for 1,000 blades | No plugs are needed. Direct CAD to mold |
| Wires are embedded into the fiberglass surface by hand during mold fabrication to heat the surface | Air passages are incorporated into the design of the mold to accommodate heated air which is cycled throughout the mold |

*One section of the wind turbine blade mold manufactured on the BAAM-CI from 20% CF-ABS pellets*
What’s next

• Bigger, faster and better
  – Bigger: CRADA with Ingersoll on development of WHAM
  – Faster: from 100 lb/hr to over 1000 lb/hr
  – Better: long fiber/continuous fiber, fiber alignment with microstructure control, resins and reactive polymers. End goal is to transition from tooling to end use parts.
Thank You

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